

# LIGHT STOPS FROM EXTRA DIMENSIONS

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In supersymmetric models the mass of the stops can be considered as the naturalness measure of the theory. Roughly, the lighter the stops are, the more natural the theory is. Both, the absence of supersymmetric signals at experiment and the measurement of the Higgs mass, put scenarios with light stops under increasing tension. I will present a supersymmetry breaking mechanism of the Scherk-Schwarz type that, by introducing extra  $SU(2)_L$  triplets in the Higgs sector, is able to generate the correct Higgs mass while keeping stops light.

## 1 Introduction

In BSM theories and because of the strength of the top yukawa coupling, top partners can be (roughly) considered as a measure of the naturalness of the theory. In the particular case of supersymmetry these top partners are the scalar top quarks, which, when appearing, are expected to cancel the dangerous contributions to the Higgs potential that destabilize the Electroweak VEV. A natural version of supersymmetry as a UV completion of the SM would therefore require stops to be as light as possible to minimize fine-tuning.

However, light stops (below 1 TeV) are difficult to encompass within the current experimental situation. Through dominant 1-loop contributions, stop masses and the mixing in the stop sector are critical in the predicted value of the Higgs mass. They are required to be as large as possible in order to fit the 125 GeV experimental measurement<sup>1</sup>. On top of that, searches for superpartners at the LHC have returned null results up to now. Since common models of soft SUSY breaking and RGE correlations tend to relate the masses of superpartners, bounds on other sparticles will constrain the SUSY breaking mechanism, affecting the value of the stop mass. For instance, normally, the heavier the gluino, the heavier the stop.

As the quest for a natural theory of the EW scale by means of supersymmetry is becoming harder, it is mandatory for BSM model builders to explore non minimal realizations of supersymmetry. This was our aim when working on the model that I now present. It was introduced in Ref.<sup>2</sup>, to which, together with Refs.<sup>3,4</sup>, I refer the reader for technical details.

## 2 The model

We start by embedding the MSSM in a 5D space-time setup where the extra dimension is the orbifold  $S^1/Z_2$  with two four-dimensional (4D) branes at the fixed points  $y = 0$  and  $y = \pi R$ <sup>a</sup>. The gauge and Higgs sectors, as well as the first and second generation of matter (and the right-handed stau<sup>b</sup>), propagate in the bulk while the rest of the third generation matter is localized at the  $y = 0$  brane. A Scherk-Schwarz twist breaks  $N=1$  Supersymmetry. It consists in imposing to the (superpartner) 5D fields a nontrivial twist ( $\omega$ ) under a  $2\pi$  translation on the fifth dimension. This breaking felt by the bulk fields will then be translated to the fields on the brane radiatively. These are the main features of the scenario:

- The Higgsino zero mode has a Dirac mass equal to  $\omega/R$ , by which there is no need of introducing a superpotential  $\mu$ -like term as in the MSSM. There is no  $\mu$ -problem.
- The lightest ( $n = 0$ ) modes of the fields in the bulk have tree-level masses that are either zero,  $\omega/R$ ,  $2\omega/R$  or  $1/R$  (see Fig. 1). Vanishing masses correspond to SM-like fields.

<sup>a</sup> $R$  is the radius of the circle  $S^1$ .

<sup>b</sup>We are considering  $\tilde{\tau}_R$  propagating in the bulk in order to avoid bounds on heavy stable charged particles<sup>5</sup>.

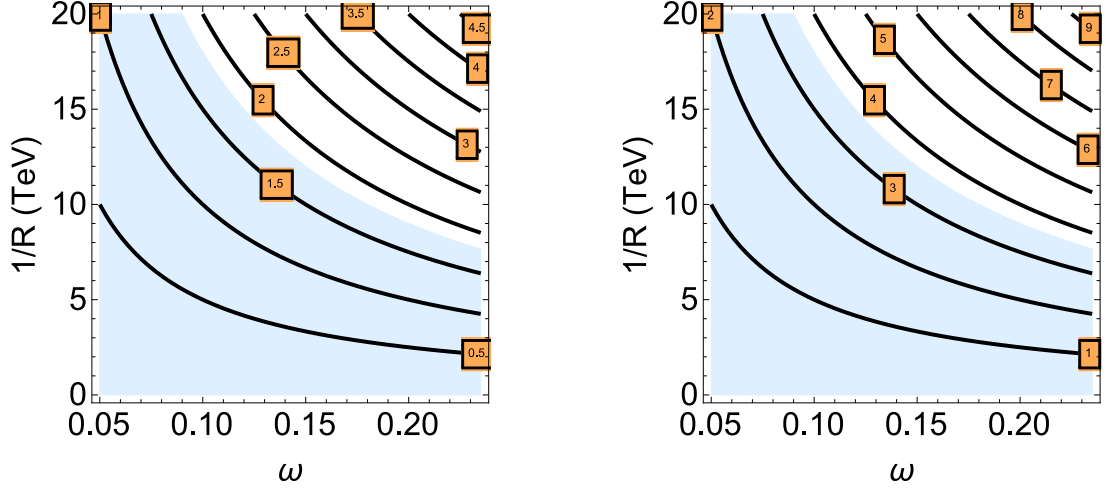


Figure 1 – Contour plots of the tree-level masses of the bulk fields sensitive to the SS mechanism. Labels are in TeV units. Left panel: First and second generation sfermions, right-handed stau, gauginos and Higgsinos. Right panel: Charged and neutral heavy doublet Higgses. In light blue the region with gluino mass  $m_{\tilde{g}} < 1.8$  TeV, in tension with LHC bounds.

- States localized in the brane, are naturally light as their tree-level masses are vanishing. Their one-loop radiative masses from KK modes are finite and can be interpreted as finite threshold effects after integrating out the heavy modes (see left panel of Fig. 2).
- At tree-level the theory predicts a 4D massless Higgs doublet with a flat potential while the rest of the Higgs sector is heavy.

The last point is what generates the drawbacks of the minimal picture in the SS SUSY breaking paradigm. The 4D effective potential that is left when integrating out KK modes is the following,

$$V_{SM} = (m_{\text{tree}}^2 + \Delta_h m^2) |h^{(0)}|^2 + (\lambda_{\text{tree}} + \Delta\lambda) |h^{(0)}|^4 + \dots, \quad (1)$$

where the value  $m_{\text{tree}}$  depends on the choice of SS twist (in our case  $m_{\text{tree}} = 0$ ) and  $\lambda_{\text{tree}}$  on the structure of the Higgs sector.  $\Delta_h m^2$  and  $\Delta\lambda$  correspond to loop order contributions.

From the potential shown above we can identify two issues:

- EWSB:** As stated above, since we have  $m_{\text{tree}} = 0$ , EWSB has to proceed via radiative corrections. At one-loop, there are gauge corrections that feed  $\Delta_h m^2$  which are positive, thus preventing EWSB<sup>c</sup>.
- Higgs mass:** As both stop soft masses and trilinear stop mixing parameter are 1-loop suppressed, their radiative correction to the Higgs quartic coupling is too small to reproduce the experimental value  $m_h \simeq 125$  GeV.

To solve the EWSB and Higgs problems we consider the scenario where the Higgs sector is extended by hyperchargeless  $SU(2)_L$  triplets propagating in the bulk<sup>d</sup>. It turns out that triplets introduce new radiative corrections to the mass of the Higgs doublet which are negative and help in ending up with a tachyonic mass for the Higgs doublet, thus facilitating the observed EWSB in a somewhat wide parameter region (see right panel of Fig. 2). Also, the presence of triplets enhances the tree-level Higgs quartic coupling in the effective theory and thus makes it easy to accommodate the 125-GeV Higgs mass constraint.

<sup>c</sup>Also, stops are localized, thus massless at tree level and they do not produce any 1-loop correction to the Higgs mass proportional to  $h_t^2$  which could trigger EWSB as in the 4D MSSM.

<sup>d</sup>As we refrain from introducing any dimensionful parameter in the 4D superpotential, we do not consider the option of triplets localized on the brane. In which case the fermionic triplet components would be too light to overcome the chargino mass bound<sup>6</sup>.

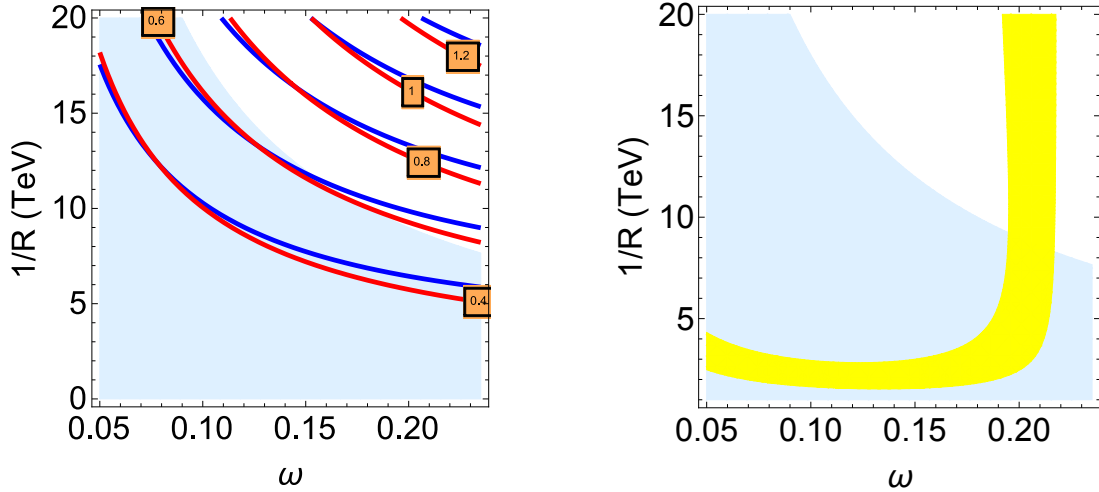


Figure 2 – Left panel: Masses of the lightest stop  $\tilde{t}_1$  and sbottom  $\tilde{b}_1$  (red and blue lines respectively). Right panel: The parameter space of the  $(\omega, 1/R)$  plane (yellow area) where the experimental EWSB with the correct Higgs mass is successfully achieved. In light blue the region with gluino mass  $m_{\tilde{g}} < 1.8$  TeV, in tension with LHC bounds.

### 3 The low energy theory

Below the energy scale of the bulk fields with masses  $\mathcal{O}(\omega/R)$  we are left with

$$\text{SM} + \sigma^{(0)} + \tilde{\ell}_3 + \tilde{t}_{1,2} + \tilde{b}_{1,2}. \quad (2)$$

In this setup the tau sneutrino ( $\tilde{\nu}_\tau$ ) is the LSP. The  $\tilde{\nu}_\tau$  is not a good dark matter candidate as it would provide the observed relic abundance for a (small) mass range that is nevertheless ruled out by direct detection experiments<sup>7</sup>. In the remaining mass region, its relic density has to be somehow reduced<sup>e</sup>.

Even though the gluino is not part of the low-energy theory, the most robust constraint to the parameter space of the model is provided by the gluino direct searches. From early 13-TeV data, ATLAS and CMS set the bound on  $m_{\tilde{g}}$  at 1.8 TeV<sup>9,10</sup>. Since the whole spectrum mostly depends on just two parameters,  $\omega$  and  $1/R$ , and in particular  $m_{\tilde{g}} = \omega/R$ , the gluino mass bound constrains the low energy theory. In particular, the gluino bound forces the mass of the stops and sbottoms to be roughly above 550 GeV and the scalar triplet, stau and tau sneutrino to be heavier than around 250 GeV. Of course, by excluding heavier gluino masses we will also be able to set stronger bounds on third-generation squarks, the triplet and the stau doublet.

As we are dealing with a heavy LSP with a mass typically above 300 GeV, the LHC bounds from stop searches are very mild or even absent<sup>11</sup>. In addition, considering usual bounds is a conservative assumption; in this model the topology of the stop decays is different from what is expected in MSSM-like scenarios. Because the stop is lighter than all neutralinos and charginos, it decays to off-shell states such that the final signature is a multi-body decay for which the current stop bounds can be very much softened<sup>12</sup>. Bounds on sbottoms are more severe than those on stops (for LSP masses below 400 GeV, ATLAS and CMS exclude sbottom masses up to 900 GeV<sup>13,14</sup>) but they suffer from the same softening mentioned above for stops.

### 4 Summary

I have shown how extra dimensions, by means of Scherk-Schwarz SUSY breaking, can serve as a tool to minimize the fine-tuning triggered by the LHC constraints on minimal supersymmetric

<sup>e</sup>This is possible if the sneutrinos do not reach thermal equilibrium before their freeze out, or an entropy injection occurs at late times (see e.g. Ref. <sup>8</sup>). Alternatively, decays such as  $\tilde{\nu}_\tau \rightarrow \tau \bar{\tau}$  can provide the desired dilution. These could in principle be generated by operators like  $LLE$  that introduce a small R-parity violation.

extensions of the Standard Model. In order to solve the EWSB and Higgs mass drawbacks of the Scherk-Schwarz paradigm,  $Y = 0$   $SU(2)_L$  triplets propagating in the bulk are introduced, these provide radiative corrections that trigger EWSB and enhance the tree level Higgs mass.

Due to the mass hierarchy between fields that propagate in the bulk and fields localized in the brane, most of the new-physics sector is decoupled from EW-scale processes, in agreement with experiments. However some superpartners, tightly linked to naturalness and/or properties of the Scherk-Schwarz twists, have to be light and populate the low-energy particle content of the theory, which eventually consists of the Standard Model degrees of freedom plus a scalar triplet, the third-generation of squarks and the doublet of sleptons.

Since gluino bounds are robust and quite generic, the most stringent constraint to the model comes from gluino searches. Nevertheless, other experimental signals could be used to test it. In the short term, searches for disappearing tracks or fermiophobic scalars are the most promising for probing part of the parameter space. Searches for the third generation of squarks are also important but it is challenging to apply their bounds to the present scenario where squarks have multi-body decays<sup>12</sup>.

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